NASA TECHNICAL MEMORANDUM

NASA TM X-3208

NASA TM X-3208

(NASA-TM-X-3208) IDLE EFFICIENCY AND POLLUTION RESULTS FOR TWO-ROW SWIRL-CAN COMBUSTORS HAVING 72 MODULES (NASA) 21 p HC $3.25 CSCL 21E

N75-18240

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H1/07 12829

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MARCH 1975

1. Report No. NASA TM X-3208	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle IDLE EFFICIENCY AND POLLUTION RESULTS FOR TWO-ROW SWIRL-CAN COMBUSTORS HAVING 72 MODULES		5. Report Date March 1975
		6. Performing Organization Code
7. Author(s) James A. Biaglow and Arthur M. Trout		8. Performing Organization Report No. E-8159
		10. Work Unit No. 505-03
9. Performing Organization Name and Address Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

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17. Key Words (Suggested by Author(s))		18. Distribution Statement	
Combustors Swirl cans Idle pollutants		Unclassified - unlimited STAR category 07 (rev.)	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 20	22. Price* $3.25

* For sale by the National Technical Information Service, Springfield, Virginia 22151

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SUMMARY

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A maximum combustion efficiency of 98.1 percent was achieved by radial scheduling of fuel to the inner row of swirl-can modules. Emission index values were 6.9 for unburned hydrocarbons and 50.6 for carbon monoxide at a fuel-air ratio of 0.0119. Circumferential fuel scheduling to two 90° sectors of the swirl-can arrays produced a maximum combustion efficiency of 97.3 percent. The emission index values were 12.0 for unburned hydrocarbons and 69.2 for carbon monoxide at a fuel-air ratio of 0.0130.

INTRODUCTION

This report presents the effects at engine idle conditions of module design changes and of radial and circumferential fuel scheduling on combustor efficiency and gaseous pollutant levels for two, two-row, 72-swirl-can-module combustors in a full-annular combustor test facility. Major sources of pollution in the vicinity of airports are due to emissions of (1) oxides of nitrogen during takeoff and landing and (2) unburned hydrocarbons and carbon monoxide during idle and taxi. Previous works (refs. 1 and 2) have shown that two- and three-row swirl-can combustors, having 72 and 120 modules, respectively, showed potential for reducing oxides of nitrogen during takeoff and landing. In particular, oxides of nitrogen emissions at an inlet-air temperature of 588 K, inlet total pressure of 62 newtons per square centimeter, and a reference velocity of 26 meters per second were 4.8 grams per kilogram of fuel for an average exit temperature of 1470 K. In addition the emission index values for idle pollutants for the three-row combustor (ref. 3) were significantly reduced by radial scheduling of fuel. With fuel supplied only to the inner row of swirl-cans, combustion efficiency was 98 percent and produced unburned hydrocarbons and carbon monoxide emission index values of 10 and 40, respectively.

This study expands the investigation of swirl-can combustors to include the effects of smaller combustor hydraulic radius and of supplying fuel to fewer modules on the idle performances of the two-row swirl-can combustor of reference 2. This combustor had 40 swirl-cans in the outer row and 32 swirl-cans in the inner row. Also investigated was a two-row swirl-can combustor configuration having 36 swirl-can modules in each row. The two-row configuration was tested with two different geometries and swirler open areas using both radial and circumferential fuel scheduling. The 40-32 swirl-can combustor and the 36-36 swirl-can combustor produced four models that were evaluated at engine idle conditions. The results of the tests of these four models provided information as to how combustor design changes affect idle pollutant levels (without fuel scheduling). They also provided parametric data showing the effects of both radial and circumferential fuel scheduling.

Test conditions for the 72 swirl-can combustors were inlet-air temperature, 452 K; inlet total pressure, 34.4 newtons per square centimeter; and reference velocity, 19.5 meters per second. These conditions are typical for a 30:1 pressure-ratio engine at idle. All tests were performed using Jet-A fuel.

The U.S. Customary system of units was used for primary measurements and calculations. Conversion to SI Units (System International d'Units) is done for reporting purposes only. In making the conversion, consideration is given to implied accuracy, which may result in the rounding off the values expressed in SI units.

APPARATUS

Two full annular combustor configurations having 72 swirl-can modules (figs. 1 and 2) were investigated in a housing that was 0.514 meter long and 1.06 meters in diameter. Both combustor configurations were two-row designs: the first one had 40 swirl-can modules in its outer row and 32 swirl-can modules in the inner row; the second configuration had 36 swirl-can modules in each row. Three versions of the 36-36 module configuration were tested. The inlet diffuser passage for both configurations was 12.95 centimeters long and had an exit area to inlet area ratio of 1.2. The diffuser was followed by a sudden expansion region in which the ratio of the annular flow area at the inlet plane of the swirl cans divided by the diffuser-exit area was 2.75 for the 40-32 swirl-can module combustor and 2.85 for the 36-36 swirl-can module combustor. The slightly different sudden expansion ratios for the two configurations resulted from the swirl-cans being supported in different ways. The swirl-cans for the 36-36 module design were mounted on the inner and outer liners and had a combustor burning length of 27.7 centimeters. The swirl-cans for the 40-32 module combustor were mounted on struts upstream of the liners and had a combustor burning length of 28.9 centimeters. The reference area for both configurations was 0.399 square meter.

Module Design

A typical assembly diagram of the swirl-can modules used in the test combustors is presented in figure 3. Each module consisted of a carburetor, swirler, and flame stabilizer. Fuel tubes enter the swirl-can modules from the upstream side and end approximately 0.63 centimeter from the face of the swirlers. Each module premixes fuel with air, swirls the mixture, stabilizes combustion in its wake, and provides interfacial mixing area between the bypass air through the array and the hot gases in the wake of the modules. Table I describes the modules used in the four combustors, including the individual blockage area offered by the flame stabilizers, swirler open area, swirler blade angle, and total combustor blockage. The four swirl-can designs used in the two swirl-can combustors were

(1) A 40-32 module combustor having trapezoidal flame stabilizers with a swirler open area of 1.84 square centimeters (fig. 4)

(2) A 36-36 module combustor using star-shaped flame stabilizers with a swirler open area of 1.84 square centimeters (fig. 5)

(3) The same module flame stabilizer design as (2) but with a swirler open area of 2.90 square centimeters

(4) A 36-36 module combustor using circular flame stabilizers with a swirler open area of 2.90 square centimeters (fig. 6) (the perforated plate shown in the figure was used to maintain the total combustor blockage to within ±2 percent of the other designs).

Test Facility

The annular swirl-can combustors were evaluated in a connected-duct test facility. A diagram of this facility and a sketch of the installation is shown in reference 4. Airflow rates and combustor pressures were regulated by remotely controlled valves upstream and downstream of the test section. A more complete description of the test facility is included in reference 5.

Instrumentation

Combustor-inlet pressures and temperatures were measured at the locations shown in figure 7. Combustor-exit total pressures and temperatures were measured in 3° circumferential increments by three equally spaced, traversing, five-point probes. Airflow rates were measured with an air orifice installed in accordance with ASME specifications. Fuel flow rates were measured with turbine flowmeters. Descriptions of the traversing combustor-exit probe and of the data acquisition and recording system are contained in references 5 and 6.

Combustor exhaust gas samples were obtained by means of three five-point traversing probes equally spaced between the combustor-exit temperature and pressure probes. The exhaust gas samples from the three probes were collected into a common line that was maintained at a minimum temperature of 422 K. The sample line was connected to four gas analyzing instruments (fig. 8). The instruments were capable of measuring concentrations of unburned hydrocarbons, carbon monoxide, carbon dioxide, and oxides of nitrogen. Figure 9 is a schematic diagram of the gas sampling system. The hydrocarbon content of the gas sample was measured by a Beckman model 402 hydrocarbon analyzer. The carbon monoxide and carbon dioxide concentration were determined by two Beckman model 315B nondispersive infrared analyzers. Oxides of nitrogen (NO_x) were measured by a Thermo-Electron Model 10A Chemiluminescent analyzer. This instrument provided separate measurements of nitric oxide (NO) and oxides of nitrogen (in the form of $NO + NO_2$).

PROCEDURE

Test Conditions

Tests were conducted over a range of fuel-air ratios at combustor operating conditions simulating idle for a high-pressure-ratio (30:1) turbofan engine. Nominal combustor operating conditions were inlet-air temperature, 452 K; inlet total pressure, 34.45 newtons per square centimeter; and combustor reference velocity, 19.5 meters per second. Data were obtained by scheduling fuel to the combustor in the following modes:

(1) Fuel flow to both rows of the combustor
(2) Fuel flow to the inner row
(3) Fuel flow to the outer row
(4) Fuel flow to two 90° sectors of the combustor.

Figure 10 shows the schematic diagram of the four idle operating modes of the test combustors.

Calculations

Combustion efficiency. - Combustion efficiency was determined by exhaust gas analysis using the equation

$$\eta_{gs} = 100 - 0.1\ EI_{HC} - \frac{EI_{CO}}{42.7}$$

Where EI_{HC} and EI_{CO} are the emission index values for unburned hydrocarbons and carbon monoxide, respectively.

Reference velocity. - Reference conditions were based on the total airflow, the inlet air density using the total temperatures and pressure at the diffuser inlet and the reference area (3992 cm^2). The reference area was measured at the point of maximum difference between the outer and inner cooling liner diameters.

Exhaust gas concentrations. - The concentration of measured exhaust gases (in ppm) was converted to a wet basis, as proposed in reference 7, and recorded in terms of an emission index EI parameter. The emission index is determined from the following equation:

$$EI_x = \frac{m_x}{m_e} \frac{(1 + f)}{f} (x) 10^{-3}$$

where EI_x is the emission index in grams of x per kilogram of fuel burned, m_x is the molecular weight of x, m_e is the average molecular weight of exhaust gases, f is the metered fuel-air ratio, and (x) is the measured concentration of x in ppm.

RESULTS AND DISCUSSION

The performances of two of the experimental 72-swirl-can-module combustors in a full annular test facility and their design changes were evaluated at idle conditions typical of a 30:1 pressure-ratio turbofan engine. Significant improvements in combustion efficiency and accompanying reductions in exhaust pollutants were realized by radial and circumferential scheduling of fuel and changes in module design. The effects of combustor design and fuel scheduling are discussed in the next sections.

40-32 module combustor. - Figure 11 presents the effect of fuel-air ratio on combustion efficiency. With all the modules supplied with fuel combustion, efficiencies were low, varying from 76 to 88 percent. Supplying fuel only to the outer row produced no significant improvement in efficiency. But, when fuel was supplied only to the inner row, combustion efficiency increased and varied from 94. 8 to 97. 3 percent. The low combustion efficiencies with fuel flow to both rows is typical of the lower efficiency values obtained with lean primary-zone combustors during idle. In addition, low fuel-injection pressure may have resulted in poor fuel distribution and atomization at the lowest fuel-air ratio. The low fuel injection pressure was a result of using the same fuel orifice that was sized for the fuel requirements at the simulated takeoff and landing conditions of reference 2.

Low fuel injection pressure does not appear to be a contributing factor to the low efficiencies obtained when fuel was supplied only to the outer swirl-can row. Although the efficiency is increased at the lowest fuel-air ratio tested, there is no significant improvement in efficiency at the higher fuel-air ratios. The most likely causes of the low efficiencies were the quenching and blowout of several combustor modules because the outer row of swirl-cans were in direct line with the diffuser exit and because of the particular flame stabilizer geometry used. The location of these outer modules in a high airflow region and the flame stabilizer geometry (figs. 1 and 4) caused them to have poor combustion stability and decreased mixing. Figure 1 shows that the outer row of modules is directly in line with the diffuser exit and that the inner row is partially sheltered from direct air impingement.

Fuel scheduling to the inner row of swirl-can modules was very effective. Combustion efficiency varied from 94. 8 percent at a fuel-air ratio of 0. 0086 to a maximum of 97. 3 percent at a fuel-air ratio of 0. 0127. The good combustion efficiency was attributed to a number of factors, which included (1) greater local fuel-air ratios resulting from the fewer inner-row swirl cans receiving more fuel, (2) larger flame stabilizer blockage resulting in good combustion stability, and (3) reduced quenching due to swirl-can locations in a zone of low air velocity.

36-36 module combustors. - Figure 12 presents the data for the 36-36 combustors and the effects of varying fuel-air ratio and module design on combustion efficiency. For ease of comparison, the data for the 40-32 module combustor are included in all figures except 12(d), which shows circumferential fuel scheduling. Figure 12(a) shows that a wide range of combustion efficiencies was obtained with fuel distribution to both rows of the combustor modules. Changing the number of modules per row, swirler flow area, and flame stabilizer geometry did not produce a uniform increase in levels of efficiency but did produce a wide scattering of data. A contributing factor to this scatter was the previously mentioned low fuel manifold pressure. The low fuel pressures caused local regions to vary in fuel-air ratio, which resulted in poor atomization, quenching, and partial blowout. Employing radial and circumferential fuel scheduling (figs. 13 to 15) greatly increased the manifold pressures and enabled the effects of design changes to be evaluated.

Radial fuel scheduling to the outer row of swirl-cans (fig. 12(b) shows an increase in combustion efficiency from 86.8 to 96.5 percent at a fuel-air ratio of 0.012. This increase occurred as the flame stabilizer blockage shape was changed from trapezoids to stars. Increasing the swirler flow area produced locally leaner fuel-air ratios resulting in a nominal decrease in peak combustor efficiency. The star-shaped design reduced peak combustion efficiency to 95.5 percent at a fuel-air ratio of 0.0127, and the circular design reduced it to 95.6 percent at a fuel-air ratio of 0.0159.

Fuel scheduling to the inner row of the swirl-can modules yielded efficiencies ranging from 94.7 to 98.1 percent and were the least affected by design changes or fuel-air ratio. Figure 12(c) shows that the maximum combustion efficiency (98.1 percent) was obtained at a fuel-air ratio of 0.0118 using the 36-36 module design having star-shaped blockage and a 1.84-square-centimeter swirler open area. Also seen from the figure is that the combustion efficiencies of all the combustor designs were within ±1 percent of each other over the entire range of fuel-air ratio. The consistent high levels of efficiency for radial fuel scheduling to the inner row indicate that this mode of supplying fuel is more effective than (1) fuel flow to both rows, which lacks sufficient manifold pressure for uniform fuel distribution to the modules, and (2) fuel scheduling to the outer row, which is more dependent on flame stabilizer geometry and swirler area.

Circumferential fuel scheduling data were obtained only for the 36-36 combustor module designs and are presented in figure 12(d). The maximum combustion efficiency was 97.3 percent at a fuel-air ratio of 0.013 using the circular flame stabilizer blockage plates with a swirler open area of 2.90 square centimeters. The most noticable trend observed with the circumferential fuel scheduling was that combustion efficiency increased as (1) swirler open area increased and as (2) the flame stabililizer geometry was changed from star-shaped to circular. The increase in combustion efficiency with these changes is opposite to the trend which occurred with radial fuel scheduling to the outer combustor rows (fig. 12(b)). This reverse in trends was attributed to the difference in nonburning zones that occurs with the two modes of fuel scheduling. In radial fuel scheduling all the burning modules are in contact with a nonburning zone and are affected by leaner fuel-air ratios in this area. Circumferential fuel scheduling has only eight modules, those at the edges of the two 90° sectors, in contact with a nonburning zone.

The fact that radial fuel scheduling to the inner row produced a greater combustion efficiency than circumferential fuel scheduling is probably due to the particular module array of these combustors. In radial fuel scheduling the inner row always yielded combustion efficiency higher than the outer row and was virtually insensitive to any design feature. This indicates that the combustion was controlled more by the local airflow patterns coming from the diffuser. The high performance of the inner row was due to those modules being positioned in a low airflow rate region; conversely, the design sensitive and poor performance of the outer row indicate modules placed in a high airflow rate region. Therefore, combustion efficiencies obtained during circumferential fuel scheduling were a result of combustion in high and low flow regions. Thus, the anticipated higher combustion efficiency for circumferential fuel scheduling was not achieved and will probably always be somewhat poorer than those due to radial fuel scheduling when the combustor has separate high and low airflow zones.

Unburned hydrocarbons and carbon monoxide. - Emission index values for unburned hydrocarbons and carbon monoxide are shown in figures 13 to 16. Figure 13 shows the data for fuel flow to both rows of the combustor. The high values of emission index for unburned hydrocarbons verify the fact that poor atomization, caused by low fuel manifold pressure and low mixing rates and hence flame quenching, were the reasons for the low combustion efficiency. Figure 14 shows that radial fuel scheduling to the outer module rows, for all except the 40-32 module combustor, substantially reduced the levels of gaseous pollutants. The high levels of emission index for the 40-32 module combustor indicate the importance of the number of modules and flame stabilizer geometry in preventing quenching and partial blowout of the combustor at idle. Emission index values were the lowest with fuel scheduled in the inner row of swirl cans (fig. 15). The lowest combination of emission index values resulting in the highest efficiency of 98.1 percent were 6.90 for unburned hydrocarbons and 50.6 for carbon monoxide at a fuel-air ratio of 0.0119.

The emission index values for circumferential fuel scheduling of two 90° sectors of the 36-36 module combustors are presented in figure 19. The lowest emission index values for this mode of operation were 12.0 for unburned hydrocarbons and 69.2 for carbon monoxide at a fuel-air ratio of 0.0130. These values of emission index resulted in a maximum combustion efficiency of 97.3 percent.

Oxides of nitrogen. - The emission index values for oxides of nitrogen were low and did not exceed 3.0 over the range of fuel-air ratios and modes of fuel scheduling investigated.

SUMMARY OF RESULTS

The effects of module design changes and radial and circumferential scheduling of fuel to two 72-swirl-can-module combustors in a full annular combustor test facility were evaluated at idle conditions typical of a 30:1 pressure-ratio engine. The following results were obtained:

1. Flame stabilizer changes only slightly improved idle efficiency when fuel was supplied to both rows of the two-row combustor configurations investigated.

2. Radial fuel scheduling to the outer combustor rows substantially improved combustion efficiency (96.5 percent) at a fuel-air ratio of 0.012. Minor variations in efficiency were noted with respect to flame stabilizer design.

3. Radial fuel scheduling to the inner module row produced the highest and most consistent levels of combustion efficiency. The maximum combustion efficiency obtained was 98.1 percent. Module design changes yielded only nominal changes in combustion efficiency (about ±1 percent).

4. Circumferential fuel scheduling yielded combustion efficiencies slightly higher than those with radial fuel scheduling to the outer module row but lower than those with fuel to the inner row. The maximum combustion efficiency obtained was 97.3 percent at a fuel-air ratio of 0.0130.

5. The lowest emission index values for unburned hydrocarbons and carbon monoxide were 6.90 and 50.6, respectively. These values were achieved at a fuel-air ratio of 0.0119 using radial scheduling of fuel to the inner row of modules. The emission index values for oxides of nitrogen were nominal and did not exceed 3.0 over the range of fuel-air ratios investigated.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, December, 20, 1974,
505-03.

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TABLE I. - TWO ROW 72 MODULE SWIRL-CAN DESIGN DATA

Configuration	Shape	Inner module blockage area, cm^2	Outer module blockage area, cm^2	Swirler open area, cm^2	Swirler blade angle	Total combustor blockage, percent
40 outer and 32 inner row modules	Trapezoidal	22.06	27.41	1.84	56^o 54'	68.7
36 outer and 36 inner row modules	Star	27.93 26.12	23.67 21.86	1.84 2.90	56^o 54' 46^o 32'	69.5 66.2
	Circular	22.70	22.70	2.90	46^o 32'	67.8

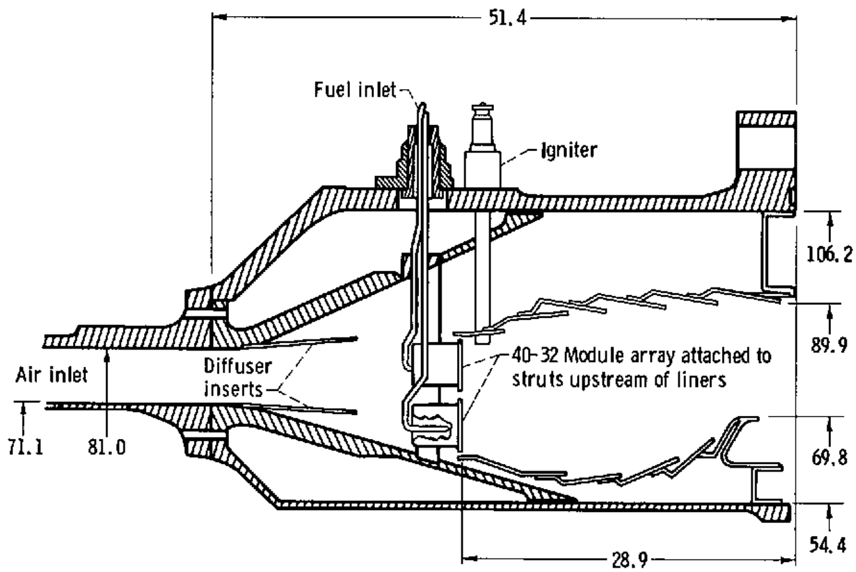

Figure 1. - 40-32 Module swirl-can combustor configuration. (Dimensions are in cm.)

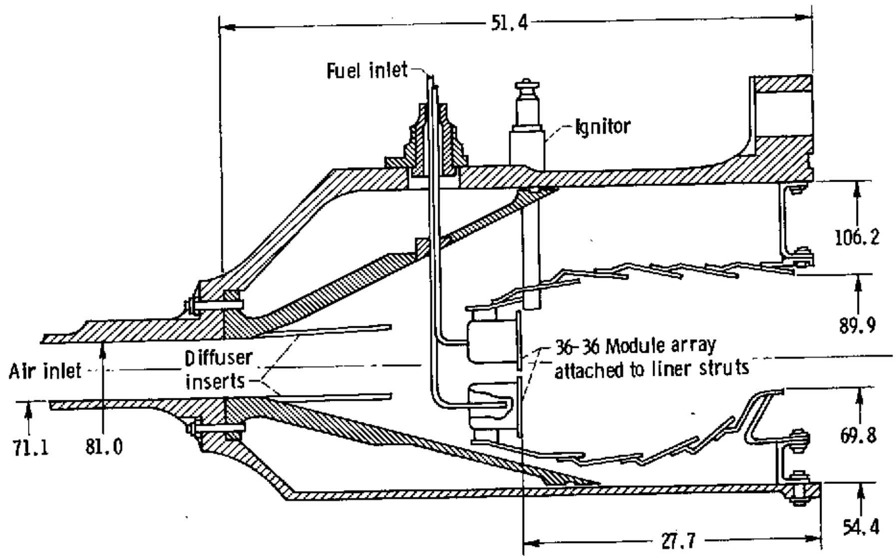

Figure 2. - 36-36 Module swirl-can combustor configuration. (Dimensions are in cm.)

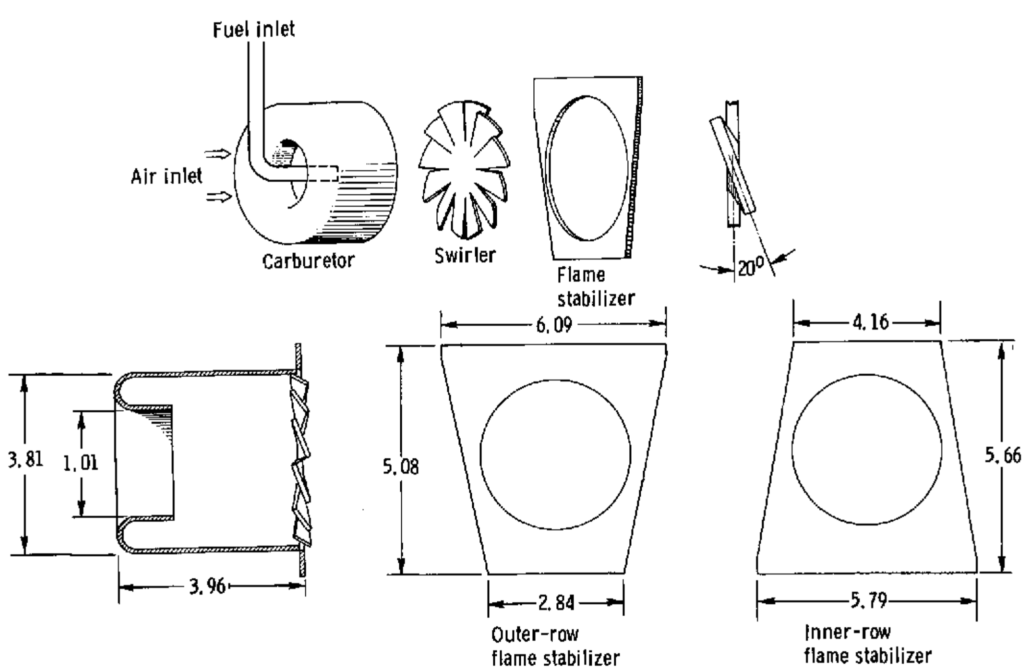

Figure 3. - 40-32 Swirl-can module details. (Dimensions are in cm.)

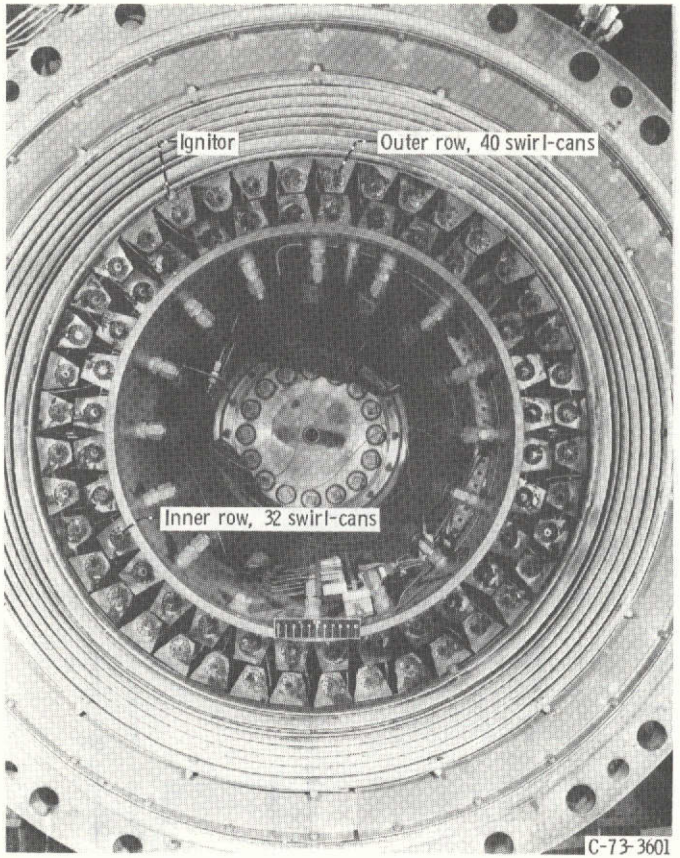

Figure 4. - 40-32 Module swirl can combustor with trapezoidal shaped blockage.

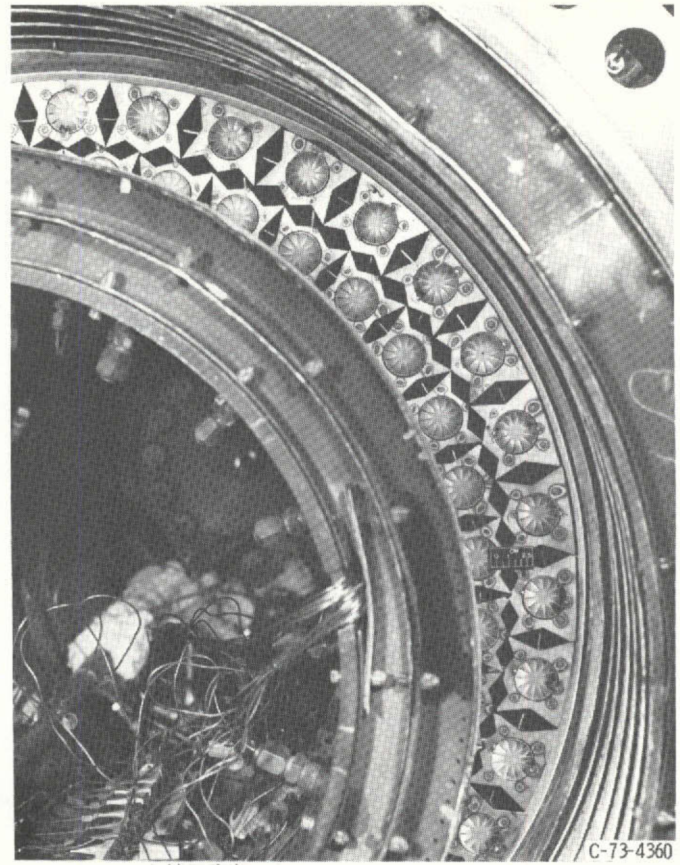

Figure 5. - 36-36 Module swirl can combustor with star shaped blockage.

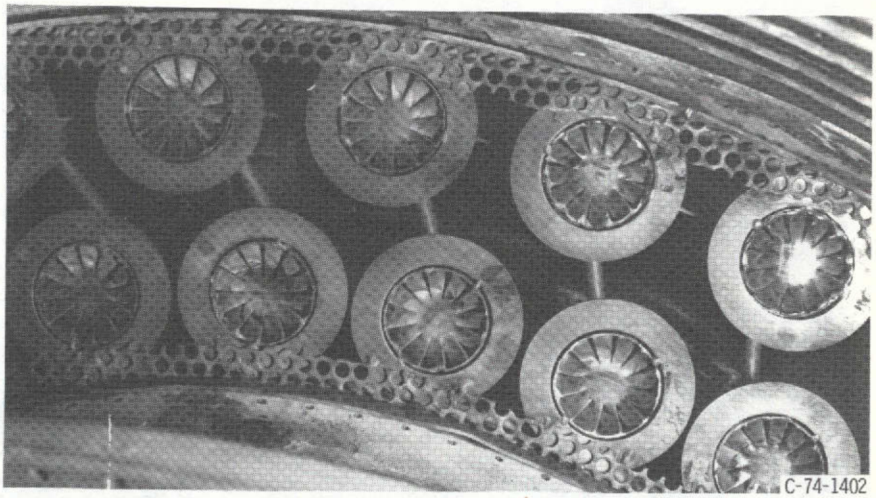

Figure 6. - 36-36 Module swirl can combustor with circular shaped blockage.

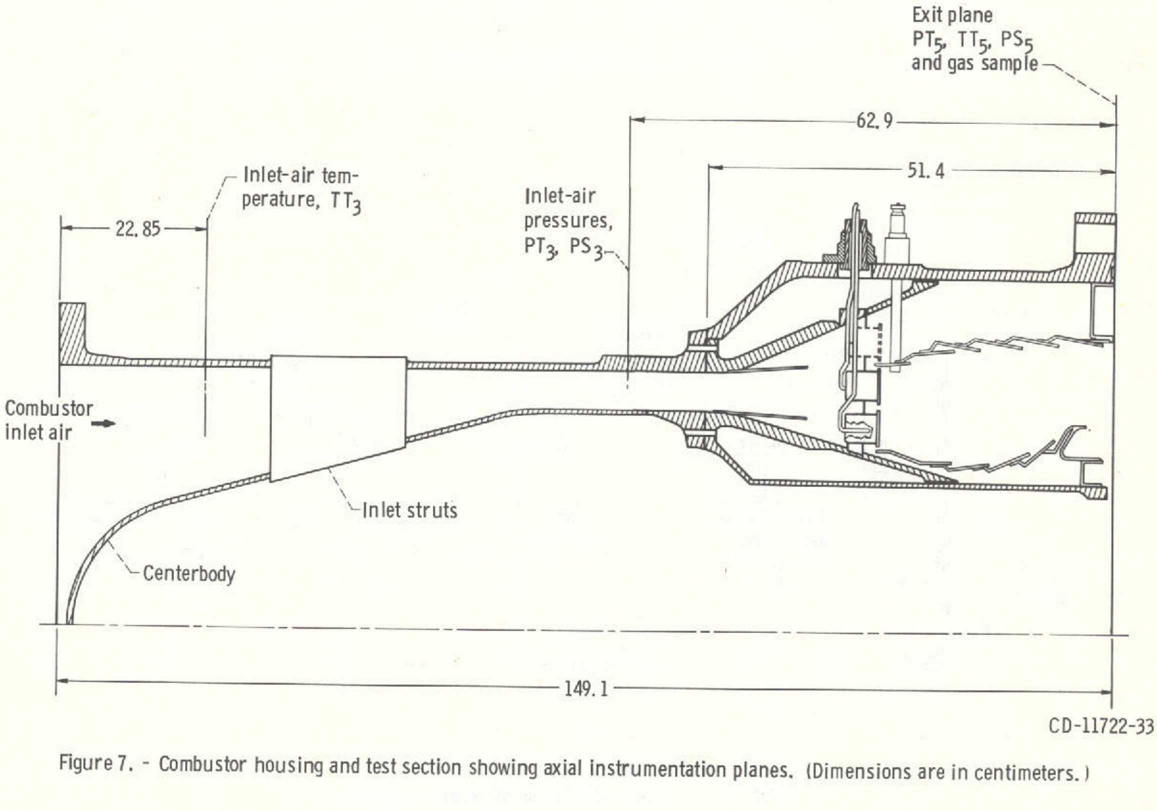

Figure 7. - Combustor housing and test section showing axial instrumentation planes. (Dimensions are in centimeters.)

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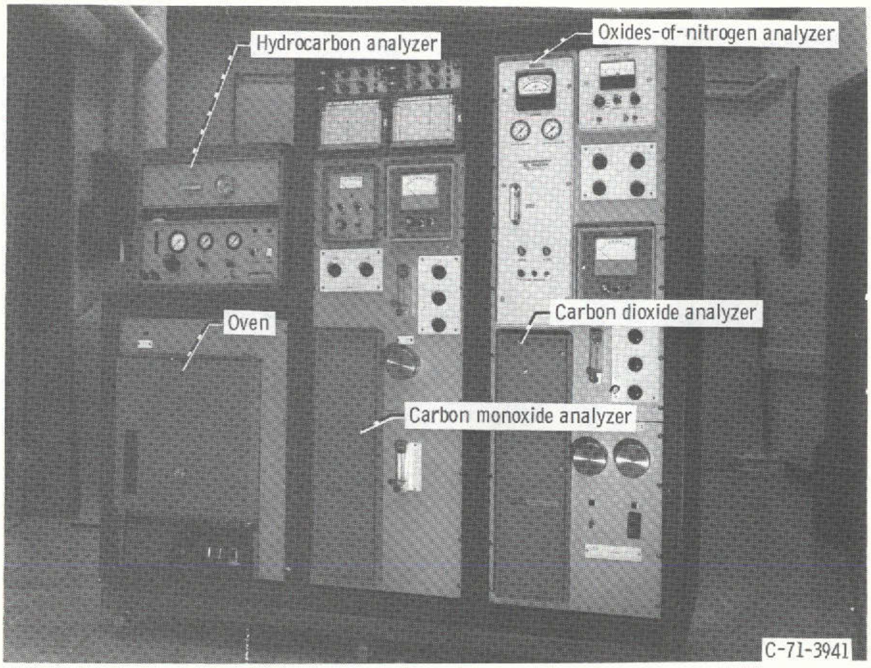


Figure 8. - Gas sampling instrument console.

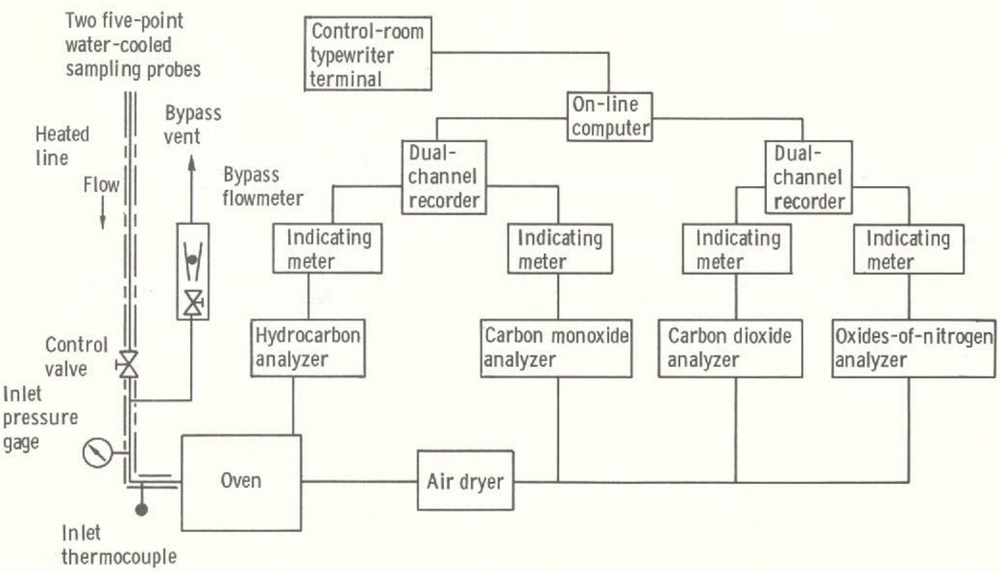


Figure 9. - Schematic diagram of gas analysis system.

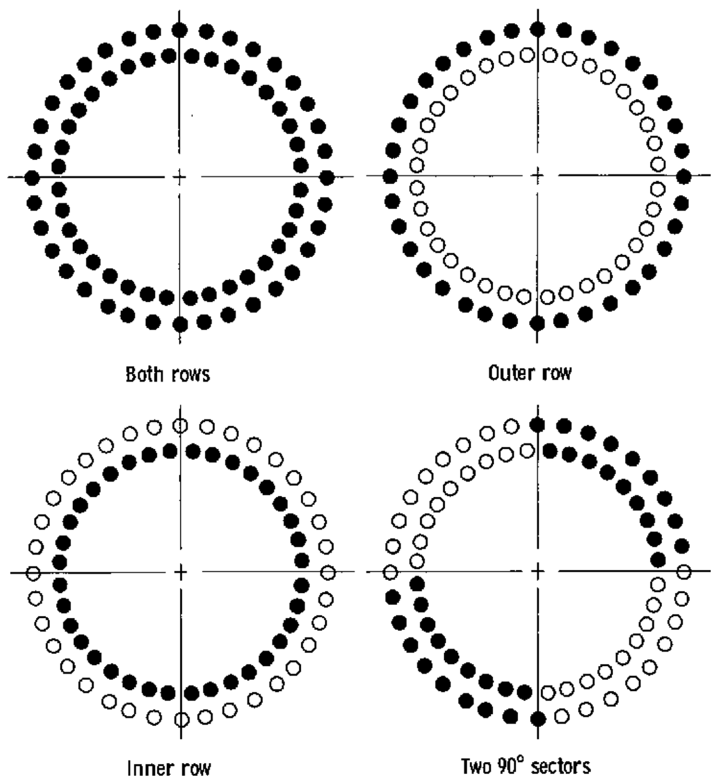


Figure 10. - Patterns of fuel distribution to test combustors.

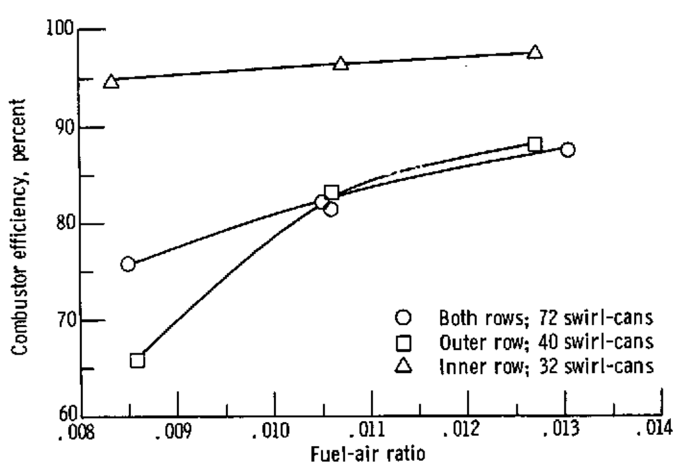


Figure 11. - 40-32 Module combustor efficiency as function of fuel-air ratio with fuel flow to both rows and to either row.

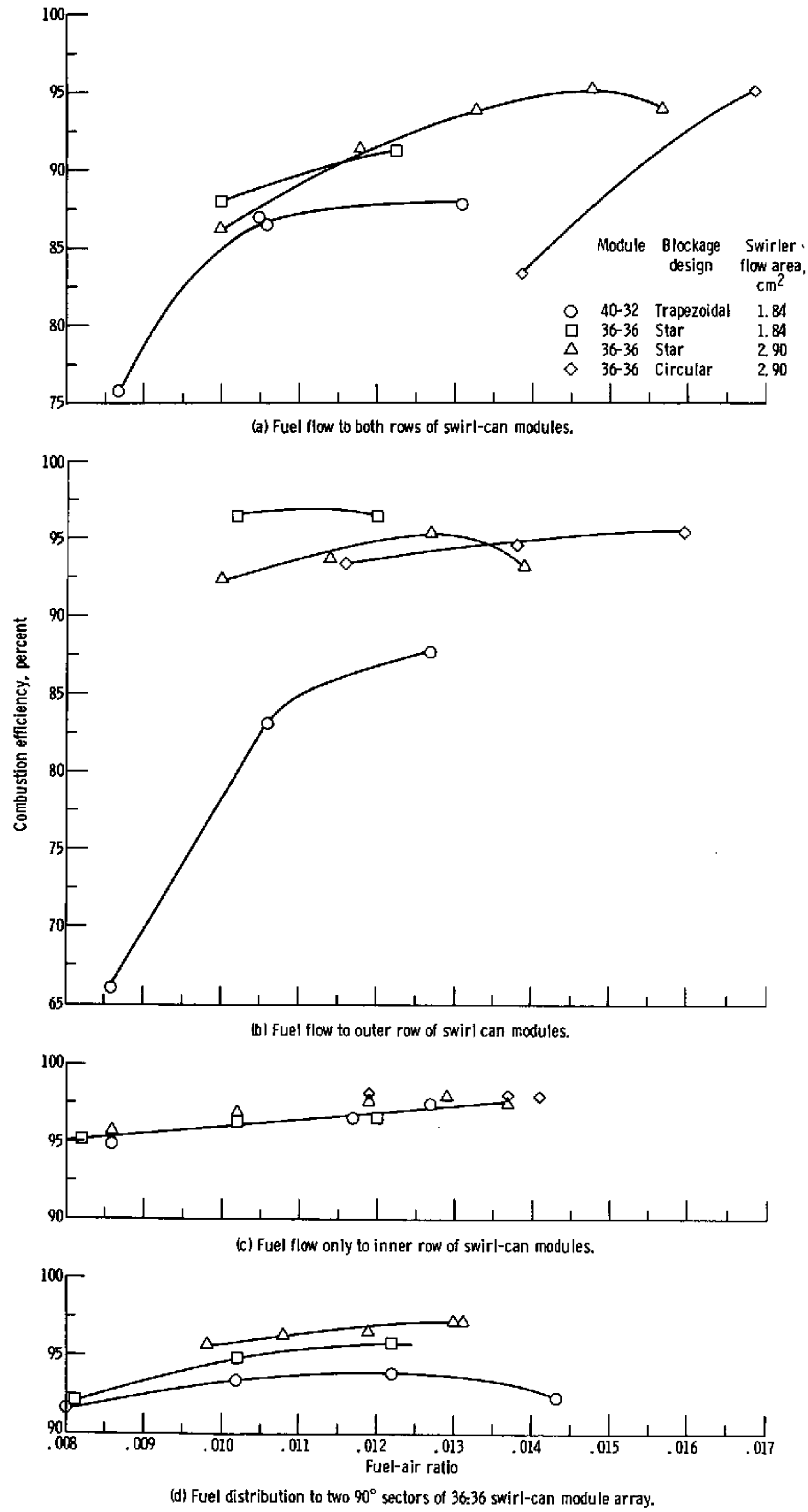


Figure 12. - Combustion efficiency as a function of fuel-air ratio for four methods of fuel scheduling.

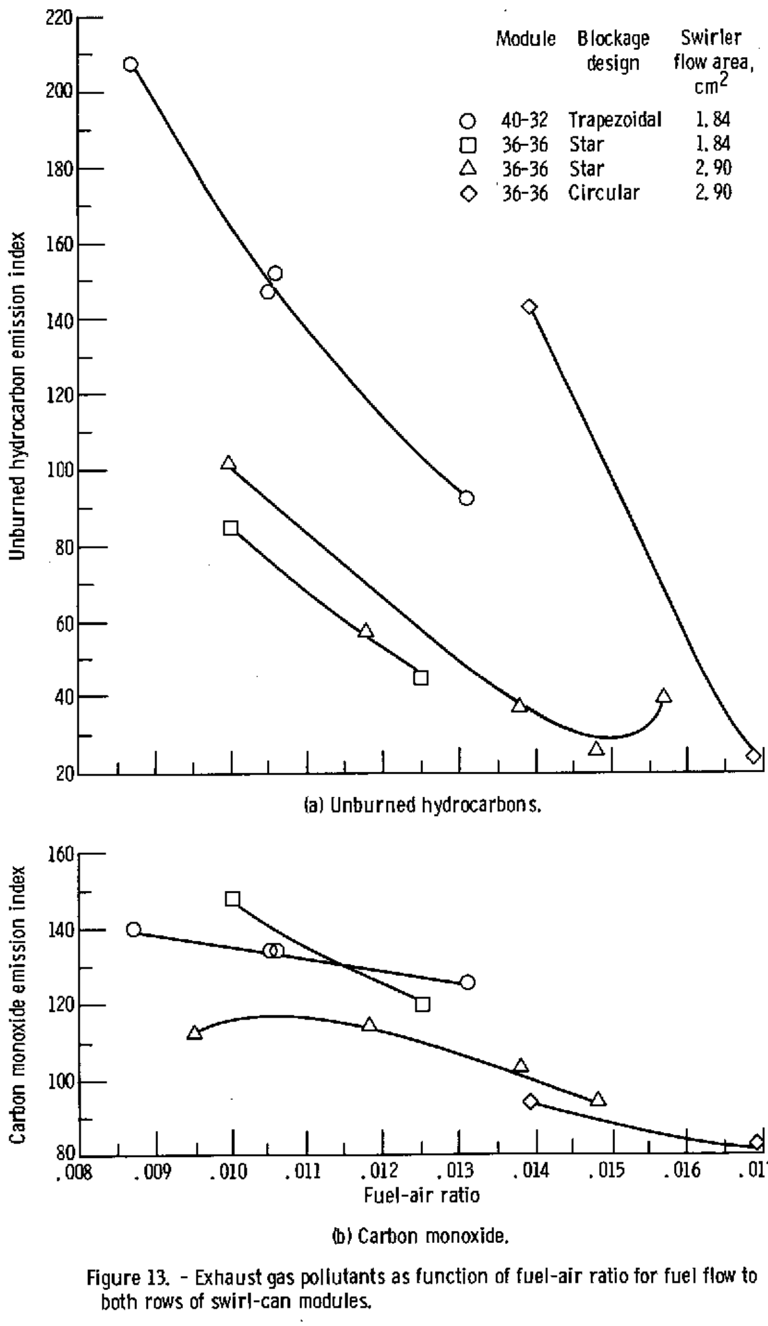


Figure 13. - Exhaust gas pollutants as function of fuel-air ratio for fuel flow to both rows of swirl-can modules.

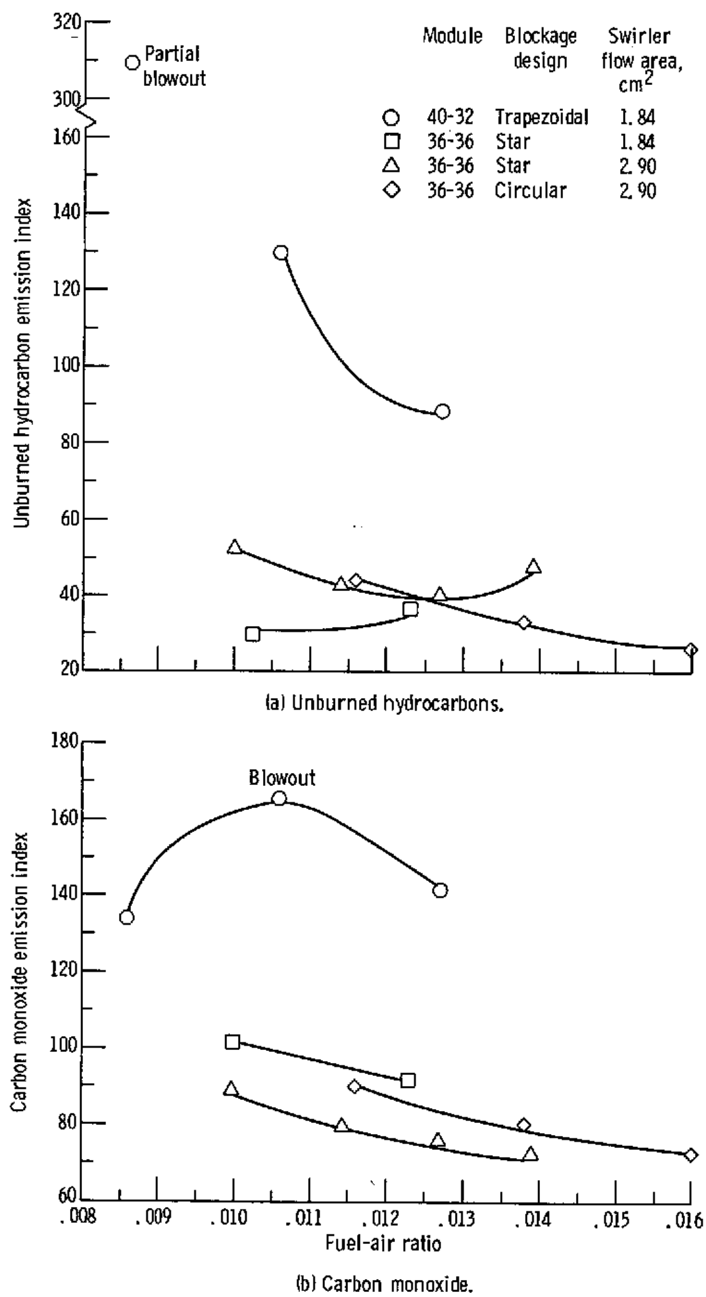
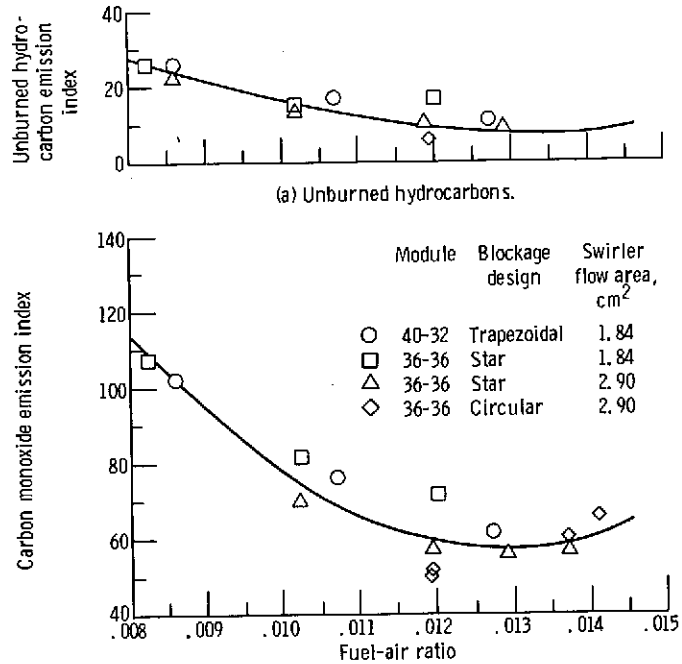


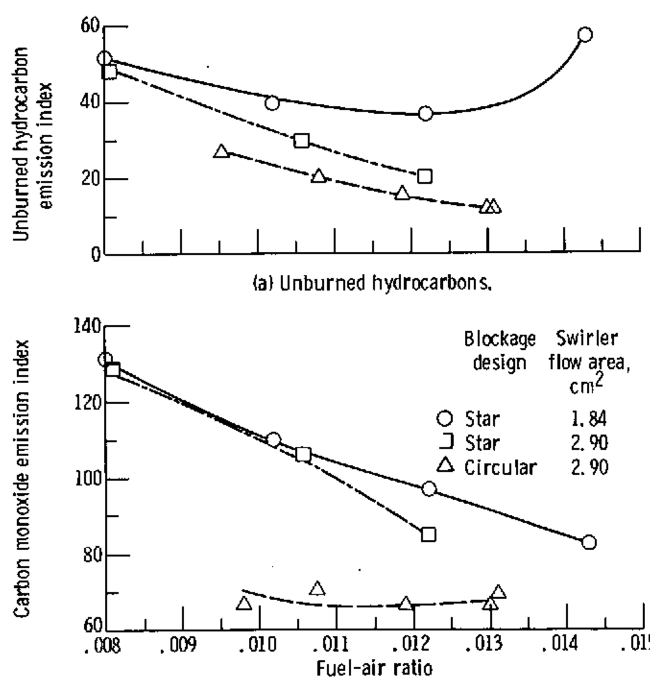
Figure 14. - Exhaust gas pollutants as function of fuel-air ratio for fuel flow to outer combustor row of swirl-can modules.



(a) Unburned hydrocarbons.

(b) Carbon monoxide.

Figure 15. - Exhaust pollutants as function of fuel-air ratio for fuel flow to inner row of swirl-can modules.



(a) Unburned hydrocarbons.

(b) Carbon monoxide.

Figure 16. - Exhaust gas pollutants as function of fuel-air ratio for fuel distribution to two 90° sectors of 36-36 module configuration.